Contaminant Hydrogeology

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Macmillan Publishing Company
New York

Maxwell Macmillan Canada
Toronto

Maxwell Macmillan International
New York Oxford Singapore Sydney

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Macmillan Publishing Company
866 Third Avenue
New York, New York 10022

Macmillan Publishing Company is part of the
Maxwell Communication Group of Companies.

Maxwell Macmillan Canada, Inc.
1200 Eglinton Avenue East, Suite 200
Don Mills, Ontario M3C 3N1

Library of Congress Cataloging-in-Publication Data

Fetter, C. W. (Charles Willard)
Contaminant hydrogeology/C. W. Fetter.
p. cm.
Includes bibliographical references and index.
ISBN 0-02-337135-8
1. Water, Underground—Pollution. 2. Water, Underground—Pollution—United States.
3. Transport theory. 4. Hydrogeology.
I. Title.
TD426.F48 1992
628.1'68—dc20 92-17787
CIP

Printing: 2 3 4 5 6 7 8 9 Year: 3 4 5 6 7

Thus values of erfc(B) range from 0 to +2, since the maximum value of erf(B) is 1.0 for 3.0 and all greater numbers.

EXAMPLE PROBLEM Assume a D of 1×10^{-9} m^2/sec and an ω of 0.5, to give a D^* of 5×10^{-10} m^2/sec. Find the value of the concentration ratio, C_i/C_0, at a distance of 5 m after 100 yr of diffusion.

1. Convert 100 yr to seconds:

$$100 \text{ yr} \times 365 \text{ days/yr} \times 1440 \text{ min/day} \times 60 \text{ sec/min} = 3.15 \times 10^9 \text{ sec}$$

2. Insert values into Equation 2.5:

$$\frac{C_i}{C_0} = \operatorname{erfc} \frac{5}{2(5 \times 10^{-10} \text{ m}^2/\text{sec} \times 3.15 \times 10^9 \text{ sec})^{0.5}}$$

3. Solve:

$$\frac{C_i}{C_0} = \operatorname{erfc}\left(\frac{5}{2.51}\right) = \operatorname{erfc} 1.99 = 0.005$$

In 100 yr, diffusion over a 5-m distance would yield a concentration that is 0.5% of the original.

From the preceding example problem it is obvious that diffusion is not a particularly rapid means of transporting dissolved solutes. Diffusion is the predominant mechanism of transport only in low-permeability hydrogeologic regimes. However, it is possible for solutes to move through a porous or a fractured medium by diffusion even if the ground water is not flowing.

2.3 Transport by Advection

Dissolved solids are carried along with the flowing ground water. This process is called **advective transport,** or **convection.** The amount of solute that is being transported is a function of its concentration in the ground water and the quantity of the ground water flowing. For one-dimensional flow normal to a unit cross-sectional area of the porous media, the quantity of water flowing is equal to the *average linear velocity* times the *effective porosity.* **Average linear velocity,** v_x, is the rate at which the flux of water across the unit cross-sectional area of pore space occurs. It is not the average rate at which the water molecules are moving along individual flowpaths, which is greater than the average linear velocity due to tortuosity. The **effective porosity,** n_e, is the porosity through which flow can occur. Noninterconnected and dead-end pores are not included in the effective porosity.

$$v_x = \frac{K}{n_e}\frac{dh}{dl} \tag{2.6}$$

where

v_x = average linear velocity (L/T)
K = hydraulic conductivity (L/T)
n_e = effective porosity
dh/dl = hydraulic gradient (L/L)

The one-dimensional mass flux, F_x, due to advection is equal to the quantity of water flowing times the concentration of dissolved solids and is given by Equation 2.7:

$$F_x = v_x n_e C \tag{2.7}$$

The one-dimensional advective transport equation is

$$\frac{\partial C}{\partial t} = -v_x \frac{\partial C}{\partial x} \tag{2.8}$$

(The derivation of this equation is given in Section 2.6.)

Solution of the advective transport equation yields a sharp concentration front. On the advancing side of the front, the concentration is equal to that of the invading ground water, whereas on the other side of the front it is unchanged from the background value. This is known as **plug flow,** with all the pore fluid being replaced by the invading solute front. The sharp interface that results from plug flow is shown in Figure 2.3. The vertical dashed line at V represents an advancing solute front due to advection alone.

Due to the heterogeneity of geologic materials, advective transport in different strata can result in solute fronts spreading at different rates in each strata. If one obtains a sample of water for purposes of monitoring the spread of a dissolved contaminant from a borehole that penetrates several strata, the water sample will be a composite of the water from each strata. Due to the fact that advection will transport solutes at different rates in each stratum, the composite sample may be a mixture of water containing the transported solute coming from one stratum and uncontaminated ground water coming from a different stratum where the average linear velocity is lower. The concentration of the contaminant in the composite sample would thus be less than in the source.

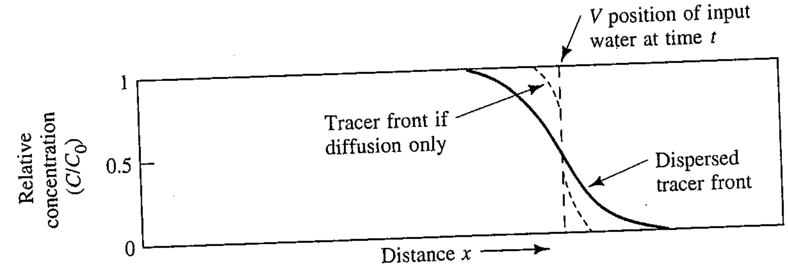

FIGURE 2.3 Advective transport and the influence of longitudinal dispersion and diffusion on the transport of a solute in one-dimensional flow. *Source:* C. W. Fetter, *Applied Hydrogeology,* 2d ed. (New York: Macmillan Publishing Company, 1988).

equation $\alpha_m = 0.0175 L_s^{1.46}$. Eventually the apparent dispersivity appears to reach a maximum value.

Stochastic methods of analysis have also been developed to analyze solute transport at the field scale. Stochastic methods are based on the variation in the hydraulic conductivity values because it is that variation that causes the solute plume to spread. The ground-water velocity depends upon the porosity as well as the hydraulic conductivity, but the hydraulic conductivity varies over a much greater range than porosity.

At the field scale the spreading due to hydraulic conductivity variation is much greater than that due to pore-scale dispersion. Both stochastic and advection-dispersion models demonstrate that the primary movement of the solute plume is due to advection. The stochastic model yields the movement of the center of mass of the solute plume from the average rate of movement of the ground water. The variance of the solute concentration about the mean position, or the second spatial moment, is also obtained from stochastic models.

If one has sufficient knowledge of the distribution of hydraulic conductivity in an aquifer, then a numerical advection-dispersion model of ground-water flow can be developed that uses a pore-scale dispersion value. This type of model has theoretical validity, because the necessary coefficient of longitudinal dispersion does not change with flow path length. It can be used to predict future solute concentrations at specific places and times. Naturally, such predictions will not be 100% accurate, because one can obviously never know the value of the hydraulic conductivity every place in the flow field.

Chapter Notation

A	Cross-sectional area
a	Width of a fracture
b	Aquifer thickness
B	$[(v_x x)^2/(2D_L)^2 + (v_x y)^2/(4D_L D_T)]^{1/2}$
C	Solute concentration
C_i	Concentration at some point x and time t
C_0	Concentration at time 0
C_R	Dimensionless solute concentration (C/C_0)
$\langle C \rangle$	Ensemble mean concentration
c_o	Constant related to anisotropy
d	Characteristic flow length for Peclet number, P
dh/dl	Hydraulic gradient
D^*	Effective diffusion coefficient
D_d	Molecular diffusion coefficient
D_i	Coefficient of hydrodynamic dispersion in the i direction
D_L	Coefficient of longitudinal hydrodynamic dispersion
D_{LM}	Coefficient of longitudinal macrodispersivity at the asymptotic limit
D_m	Field-measured (calculated) coefficient of hydrodynamic dispersion
D_T	Coefficient of transverse hydrodynamic dispersion
E	Euler number (0.577 . . .)
E_i	Exponential integral

Chapter Eight

Ground-Water and Soil Monitoring

8.1 Introduction

Methods of installing monitoring wells and collecting ground-water samples have been developed with the specific intention of obtaining a representative sample of water from an aquifer. These methods minimize the potential for the introduction of contaminants into the ground through the process of installing a monitoring well. Wells and sampling devices can be constructed of materials that have a minimum tendency to leach materials into and sorb compounds from the water sample. Ground-water samples can be collected in such a manner that dissolved gases are not lost or exchanged with the atmospheric gases. Soil samples can also be collected for classification and chemical analysis.

Methods of collecting samples of soil water are also available. Soil gas sampling can be done to give an indication of areas where volatile organic compounds are contained in the soil or ground water.

8.2 Monitoring Well Design

8.2.1 General Information

Monitoring wells are installed for a number of different purposes. During the installation of a monitoring well, a soil boring may be made or rock-core samples may be collected to determine the basic geology of the site. Prior to the design of a well, it is necessary to determine what its use will be. Some purposes of monitoring wells include the following:

- Measuring the elevation of the water table
- Measuring a potentiometric water level within an aquifer
- Collecting a water sample for chemical analysis
- Collecting a sample of a nonaqueous phase liquid that is less dense than water
- Collecting a sample of a nonaqueous phase liquid that is more dense than water
- Testing the permeability of an aquifer or aquiclude
- Providing access for geophysical instruments
- Collecting a sample of soil gas

The use for which the well is intended will dictate the design. For example, if a well is to be used for the collection of water samples, the casing must be large enough to accommodate the water-sampling device. However, the diameter should not be much larger than the minimum size, because prior to the sampling of a well, stagnant water must be removed from the casing; the larger the diameter of the casing, the greater the volume of water that must be pumped and properly disposed. The factors that should be included in the design of a monitoring well include

- Type of casing material
- Diameter of the casing
- If there will be a well screen or an open borehole
- Length of casing
- Depth of the well
- Setting and length of the well screen
- Diameter of well screen
- Type of material for well screen
- Slot opening of well screen
- If an artificial filter pack (gravel pack) is necessary
- Gradation of filter pack (gravel pack) material
- Method of installation of well and screen
- Material used to seal annular space between casing and borehole wall
- Protective casing or well vault

8.2.2 Monitoring Well Casing

All monitoring wells have a **casing,** whether they have a screen or terminate in an open borehole in bedrock. The casing is a piece of solid pipe that leads from the ground surface to the well screen or open borehole and is intended to keep both soil and water from entering the well other than through the screen or open borehole. Casing also prevents water from flowing from one aquifer horizon to another.

The diameter of the casing for a monitoring well is determined by the use for which the monitoring well is planned. If the only purpose of the monitoring well is to measure water levels, then a 1-in.-inside-diameter casing is all that is needed. An electric probe to measure water level or a pressure transducer will fit inside the 1-in. casing. Figure 8.1 shows an electric probe being lowered into a 2-in. casing.

If a well is to be used to collect a ground-water sample, the diameter of the well needs to be such that standard well-sampling equipment can fit inside. The common standard for well-sampling equipment is a nominal 2-in. diameter. This can accommodate a wide variety of pumps that can withdraw water at rates of 0.5 to 2 or 3 gal/min. Specially designed borehole geophysical equipment can also fit inside a 2-in. diameter casing. Some states mandate the casing diameter for monitoring wells. For example, the Wisconsin Department of Natural Resources requires a minimum inside diameter of 1.9 in. and a maximum inside diameter of 4.0 in., whereas the New Jersey Department of Environmental Protection requires a 4-in.-diameter well under all conditions.

For some applications, monitoring wells may be intended for several functions such as measuring water levels, collecting water samples, pumping to remove

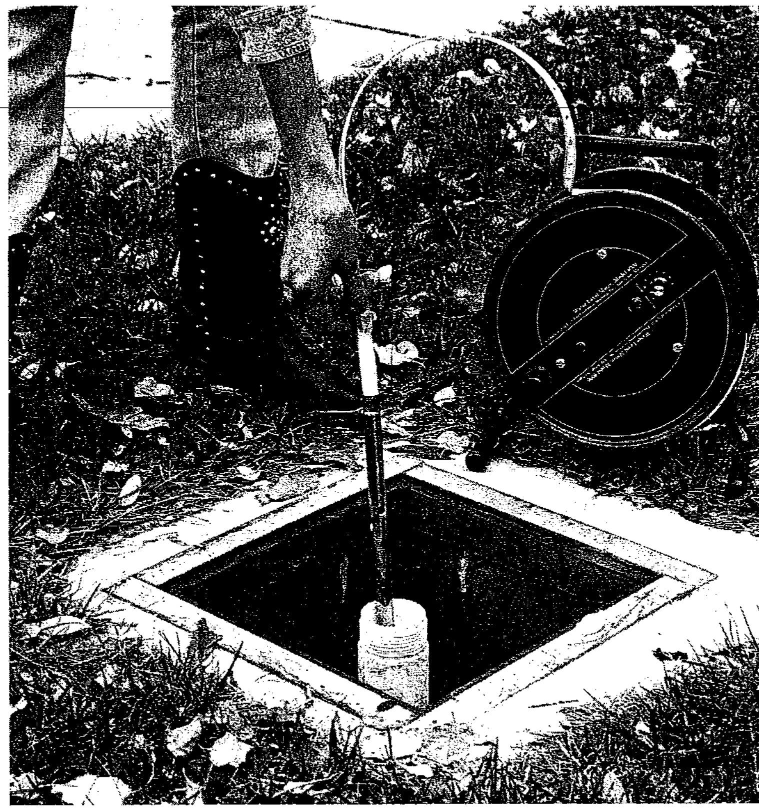

FIGURE 8.1 Electric probe used to measure water levels in monitoring wells. Photo credit: Jim Labre.

contaminated water, and perhaps floating nonaqueous phase liquids and as a part of a vapor-extraction system. These wells generally have diameters larger than 2 in. to accommodate pumping equipment with a higher-flow capacity. The actual equipment to be used determines the casing diameter.

Casing diameter can also be influenced by the depth of the well. The deeper the well, the stronger the casing and screen must be to resist the lateral pressure at the final depth and the crushing force of the weight of the length of casing. Larger diameter casing can be made with thicker walls to have greater strength. It is easier to have a straight well with stronger casing. Straight wells are important in accommodating bailers and pumps.

The outside diameter of casing is standard; however, the inside diameter is a function of the wall thickness. Table 8.1 lists the wall thickness and inside diameter for various schedules of casing. Heavier-schedule casing is stronger because it has a thicker wall. The strength of a casing also depends upon the material from which it is constructed. A schedule 5 casing made of stainless steel is stronger than a schedule 40 casing made of polyvinyl chloride (PVC), yet leaves a greater inside diameter.

TABLE 8.1 Dimensions of inside and outside diameters of well casings.

Pipe Size	Outside Diameter	Schedule 5 Wall Thickness	Schedule 5 Inside Diameter	Schedule 10 Wall Thickness	Schedule 10 Inside Diameter	Schedule 40 Wall Thickness	Schedule 40 Inside Diameter	Schedule 80 Wall Thickness	Schedule 80 Inside Diameter
Nominal 2″	2.375″	0.065″	2.245″	0.109″	2.157″	0.154″	2.067″	0.218″	1.939″
Nominal 3″	3.500″	0.083″	3.334″	0.120″	3.260″	0.216″	3.068″	0.300″	2.900″
Nominal 4″	4.500″	0.083″	4.334″	0.120″	4.260″	0.237″	4.026″	0.337″	3.826″
Nominal 5″	5.563″	0.109″	5.345″	0.134″	5.295″	0.258″	5.047″	0.375″	4.813″
Nominal 6″	6.625″	0.109″	6.407″	0.134″	6.357″	0.280″	6.065″	0.432″	5.761″

There are a number of materials used to make well casings and screens. These materials vary in chemical inertness, strength, durability, ease of handling, and cost. One must always consider the intended use of the monitoring well before selecting a material. What is the chemistry of the ground water and associated contaminants? Will any compounds present in the ground water react with any of the possible casing materials? How deep will the well be; what are the strength requirements? Is the well intended for a short-term monitoring project or will it remain in service for many years?

Well casings are available in the following materials: fluoropolymers, such as PTFE, or polytetrafluoroethylene (Teflon® is the brand name of one manufacturer of PTFE), mild steel, stainless steel, galvanized steel, fiberglass, PVC, and polypropylene. Mild or galvanized steel is often used for water-supply well casings but is not as frequently found in monitoring wells because it may react with the ground water to leach metals from the casing (Barcelona, Gibb, and Miller 1983). Polypropylene is not widely available. Most monitoring wells are made of stainless steel or PVC, with PTFE being less common. PVC casing is the least expensive. Relative casing costs for other materials, compared with PVC, are mild steel = 1.1, polypropylene = 2.1, type 304 stainless steel = 6.9, type 316 stainless steel = 11.2, and PTFE = 20.7. Type 316 stainless steel is more resistant to corrosion than type 304 under reducing conditions (Aller et al. 1989).

Stainless steel has the greatest strength, followed by mild steel. Both are also resistant to heat, but they are heavier than the plastics and are, therefore, more difficult to install. The lower strength of the plastics is compensated for by using a heavier-schedule casing that necessary with steel. Most monitoring wells are shallow enough that schedule 40 or 80 PVC has sufficient strength. PTFE is more brittle and has less wear resistance than PVC or polypropylene and is hence less durable. PTFE also has a low tensile strength and high weight per unit length, which limits its use to shallow depths. Even there, PTFE casing tends to bow under its weight when installed in monitoring wells and may not be straight and plumb. Although its nonstick properties are good in frying pans, the neat cement grout used to seal the annular space between the casing and the borehole may not bond to the PTFE casing (Nielsen 1988).

In the selection of casing material for ground-water monitoring wells, we must consider the potential chemical reactions between the casing material and the ground water. Ideally, casing material should neither leach matter into water nor sorb chemicals from water.

Reynolds and Gillham (1985) studied the sorption from aqueous solution of five halogenated organic compounds by several polymer materials. The organic compounds used were 1,1,1-trichloroethane, 1,1,2,2-tetrachloroethane, hexachloroethane, perchloroethene, and bromoform. The materials tested were PVC, PTFE, nylon, polypropylene, polyethylene, and latex rubber. Nylon, polypropylene, polyethylene, and latex rubber rapidly absorbed all five compounds. PVC absorbed all the compounds but 1,1,1-trichloroethane, although the rate of absorption was low. PTFE absorbed all the compounds but bromoform; although the rate of adsorption of three of the four compounds was low, PTFE absorbed 50% of the perchloroethylene in 8 hr.

Parker, Hewitt, and Jenkins (1990) evaluated the suitability of PVC, PTFE, stainless steel type 304 (SS 304), and stainless steel type 316 (SS 316) as casing material for monitoring metals in ground water. They evaluated the interaction of four trace elements that are of concern in ground-water studies: arsenic, cadmium, chromium, and lead. The metals were tested at concentrations of 50 and 100 $\mu g/L$ dissolved in ground water. Figure 8.2 shows the results of this study. If the concentration relative to control remains at 1.0, there is no interaction; if it drops to less than 1.0, then the element is sorbing onto the casing material; and if it rises above 1.0, the element is being leached from the casing. The PTFE was the most inert with respect to the metals, and the PVC was much better than either SS 304 or SS 316.

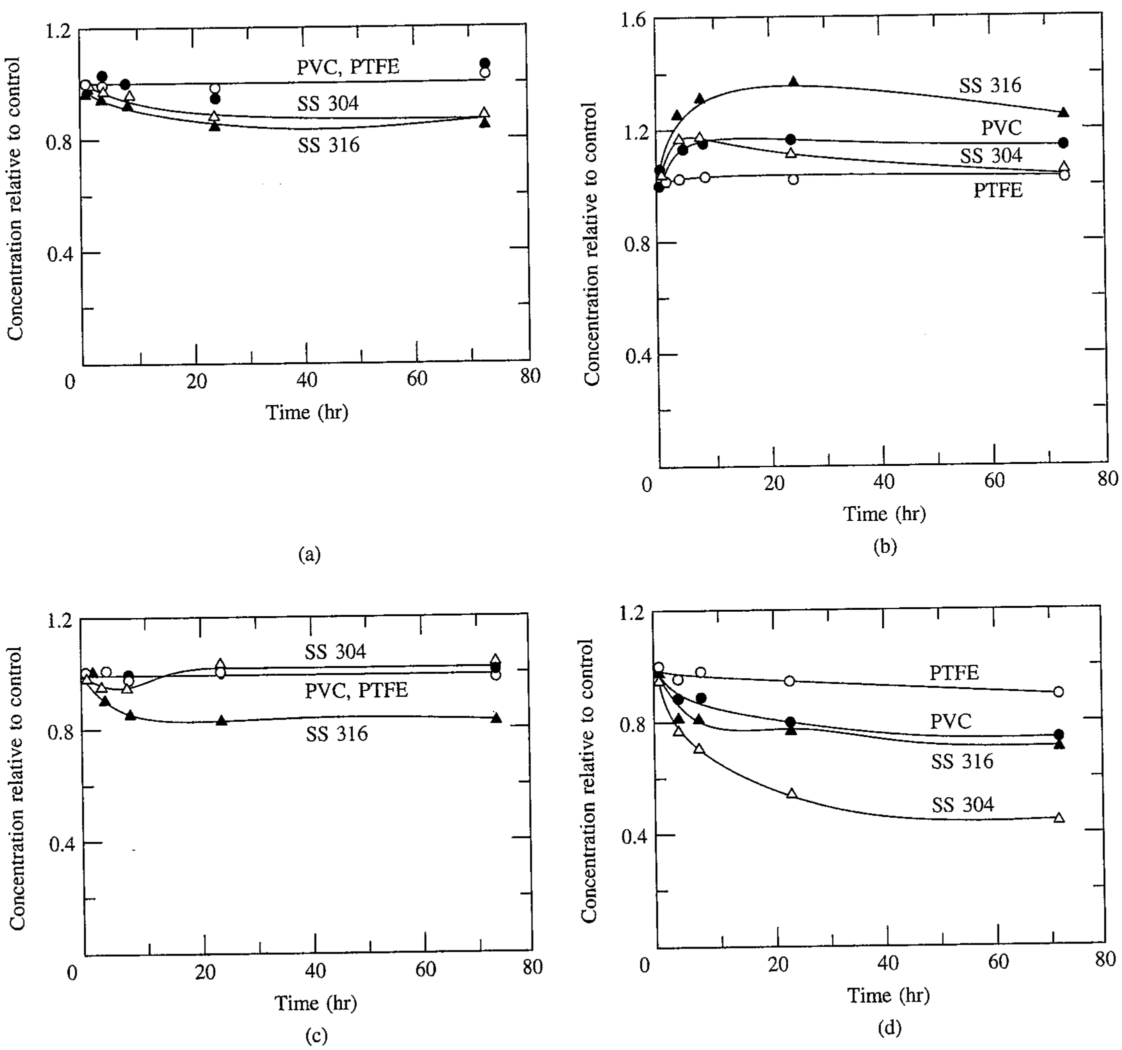

FIGURE 8.2 Sorption and leaching of arsenic, cadmium, chromium, and lead by well casings made from PVC, PTFE, type 304 stainless steel, and type 316 stainless steel. *Source:* L. V. Parker, A. D. Hewitt, and T. F. Jenkins, *Ground Water Monitoring Review* 10, no. 2 (1990):146–56. Used with permission. Copyright © 1990 Water Well Journal Publishing Co.

The interaction of several organic compounds with the same well-casing materials was also studied by Parker, Hewitt, and Jenkins (1990). Ten organic compounds were tested, including chlorinated ethenes, chlorobenzenes, nitrobenzenes, and nitrotoluenes. None of the compounds was sorbed onto either type of stainless steel. Many of the compounds were sorbed by the plastic casings, with the PTFE sorbing at a greater rate than the PVC. The amount and rate of sorption varied by compound. Figure 8.3 shows the sorption of trichloroethene by the four casing types. Clearly, stainless steel is the material of choice for monitoring organics, and PTFE is to be avoided. For a compromise material for monitoring both organics and inorganics, PVC appears to be the best. It also has the appeal of having the lowest cost. PVC manufactured specifically for well casing should be used, and it should carry the designation *NSF wc*, which indicates that the casing conforms to National Sanitation Foundation Standard 14 for potable water supply (National Sanitation Foundation 1988).

However, PVC should be avoided if certain organic compounds are present in the ground as nonaqueous phase liquids. It is reportedly soluble in low-molecular-weight ketones, aldehydes, amines and chlorinated alkanes, and alkenes (Barcelona, Gibb, and Miller 1983). Likewise, PVC casing should also never be joined with solvent-glued joints. These solvents include compounds such as methylethylketone and tetrahydrofuran and they may leach into ground water samples. Threaded joints that are machined directly onto the PVC are the preferred method of joining casing sections and casing to screen. Joints should be flush on the inside of the casing to prevent equipment being lowered into the casing from hanging up in a projecting joint.

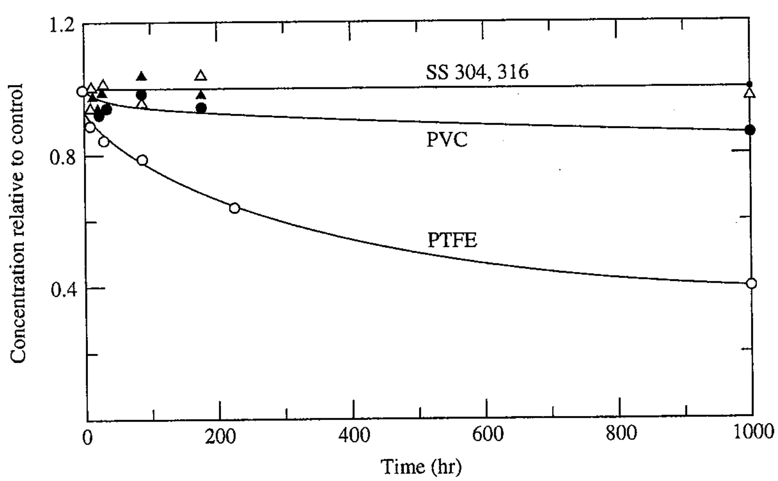

FIGURE 8.3 Sorption of trichloroethene from ground water by PVC, PTFE, type 304, and type 316 stainless steel well casings. *Source:* L. V. Parker, A. D. Hewitt, and T. F. Jenkins, *Ground Water Monitoring Review* 10, no. 2 (1990):146–56. Used with permission. Copyright © 1990 Water Well Journal Publishing Co.

8.2.3 Monitoring Well Screens

If the monitoring well terminates in an unconsolidated formation, a **screen** is necessary to allow the water to enter while keeping the sediment out. In most monitoring well applications, the well screen is the same diameter as the casing to which it is attached by a threaded coupling. Likewise, the well screen is normally made of the same material as the casing. The considerations that go into deciding the material to use for the casing also apply to the screen.

The screen will have openings to permit the water to enter. Manufactured well screen should always be used rather than hand-cut slots or drilled holes in plastic pipe. The two common screens for monitoring wells are slotted pipe, which is available in PVC and PTFE, and continuous wire wrap, which is available in stainless steel. Figure 8.4 illustrates these two screen types.

The width of the slot or wire-wrap opening is precisely controlled during the manufacture of the screen; the screen is available in a variety of opening sizes, generally ranging from 0.008 to 0.250 in. A screen with an opening of 0.010 is referred to as a 10-

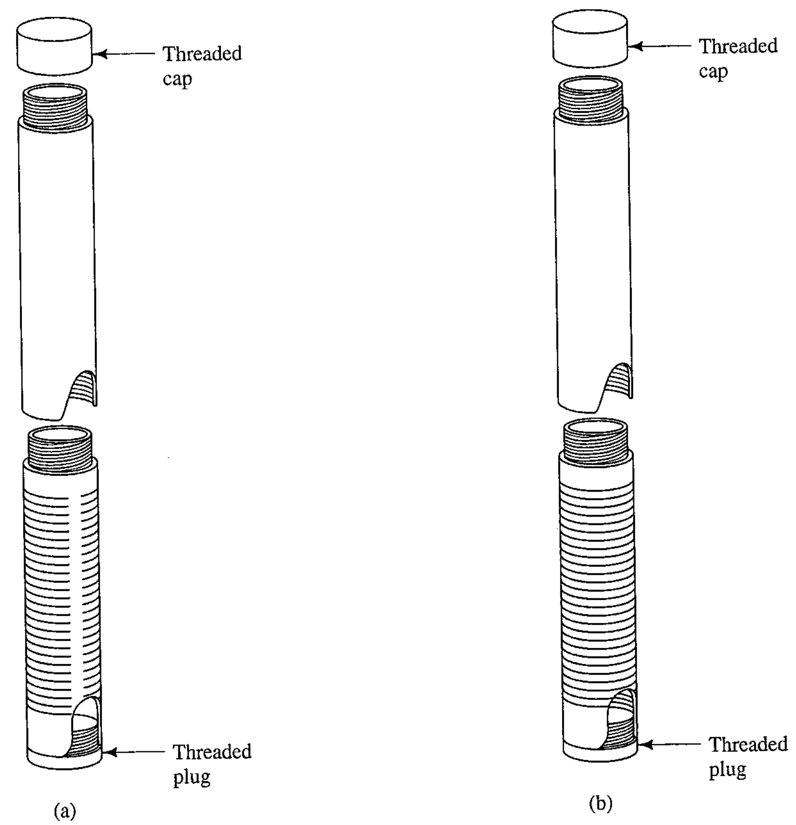

FIGURE 8.4 Slotted and continuous wire-wrapped monitoring well screens.

slot screen. Many manufacturers carry only a limited number of slot sizes in stock—for example, 10- and 20-slot. Since the casing and screen are typically ordered in advance of the well construction, the hydrogeologist usually has settled on a standard design prior to going on the job.

8.2.4 Naturally Developed and Filter-Packed Wells

The casing and screen may be placed in the borehole and the native sediment allowed to cave around the screen. This is called a **naturally developed well** and is often used in sandy sediment with very limited amounts of silt and clay present. At least 90% of the sediment should be retained on a 10-slot screen before a naturally developed well is considered (Aller et al. 1989). When water is withdrawn from such a well, it may initially be cloudy due to suspended silt and clay, but the water should eventually clear as the fines near the screen are removed by a process called well development. In a naturally developed well the slot size is selected to allow some of the fine sediment to enter the well during development; this leaves only the coarser sediment outside the screen.

In designing a water well, it is very important that the well be hydraulically effective—i.e., there should be a minimal loss of energy as the water flows into the well. The selection of the slot opening for naturally developed water wells is very important and is based on a grain-size distribution curve of the sediment opposite the well screen. Monitoring wells are designed to retain much more of the natural formation than water wells because they are much more difficult to develop (Driscoll 1986). Monitoring wells are not usually designed with the precision necessary for a water-supply well. The well should be hydraulically efficient as well as being as clear of silt and clay as possible. If preliminary investigations indicate that the aquifer to be monitored has reasonably coarse sand or gravel and few fines, a standard slot size may be preselected for all the monitoring wells. Ten-slot screen is frequently used under these conditions.

If the formation is cohesive—that is, has a high clay content—or if it is sandy with a high silt content, it will be necessary to use an **artificial filter pack.** Filter-pack material is medium to coarse sand that is predominately silica with no carbonates. It is mined and graded to have a specific grain-size distribution. Manufactured filter-pack material comes washed and bagged and is far preferable to native sand as artificial filter pack. The filter-pack material is placed in the borehole opposite the well screen. Its purpose is to stabilize the natural formation and keep it out of the screen. This will reduce the amount of silt and clay that enters the well when it is developed.

The grain size of the filter-pack material is based on the nature of the formation opposite the screen. If the formation is fine sand, then the grain-size distribution is determined. The filter pack material should have an average grain size that is twice the average grain size of the formation and have a uniformity coefficient (ratio of 40% retained size to 90% retained size) between 2 and 3 (Driscoll 1986). The screen-slot opening is then selected to retain 90% of the filter pack. The minimum practical slot size for monitoring well screens is 0.008 in. Figure 8.5 shows a grain-size distribution curve for a filter-pack material designed for an eight-slot screen. If the monitoring well is in silt or clay, all one can do is install an 8 slot screen and appropriate filter pack.

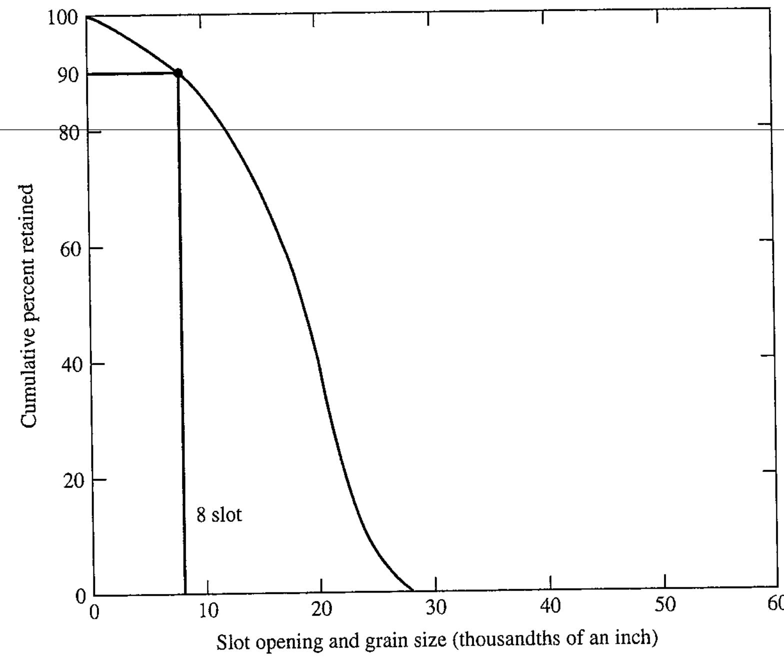

FIGURE 8.5 Grain-size distribution curve used to select an eight-slot screen for a monitoring well.

The filter-pack material should be 2 to 3 in. thick. This means that a 2-in.-diameter well screen should be installed in a borehole 6 to 8 in. in diameter. The filter-pack material is normally extended 2 or 3 ft above the top of the well screen to allow for settlement of the material during development.

8.2.5 Annular Seal

The **annular space** in the borehole above the filter pack must be sealed to prevent the movement of surface water downward to the filter pack. It may also be sealed to prevent vertical movement of ground water from one zone to another or to isolate a discrete sampling zone. The seal should be made of a material that has a low permeability, bonds well to the natural formation and the casing, and expands after it has been emplaced to ensure a tight seal. It should set up within a day or so and be durable and permanent.

Materials typically used for an annular seal are bentonite pellets, granular bentonite slurry, neat cement grout, bentonite-sand slurry, and neat cement grout with a powdered bentonite additive.

Neat cement grout is a mixture of 94 lb of type I Portland cement with 5 to 6 gal of water. Granular bentonite slurry is a mixture of 30 lb of untreated bentonite powder mixed with 125 lb of untreated bentonite granules with 100 gal of water. Bentonite-cement grout is a mixture of 5 lb of untreated powdered bentonite with 94 lb of type

I Portland cement and 5 to 6 gal of water. Bentonite-sand slurry is a mixture of 55 lb of untreated powdered bentonite with 100 gal of water and 10 to 25% sand by volume to make a slurry that weighs 12 lb/gal. All water used to make these slurries should be from a source that is fresh and known to be uncontaminated and free from floating oil.

Bentonite is a clay containing at least 85% sodium montmorillonite; it will swell to several times its original volume when thoroughly hydrated. This hydration takes place below the water table. However, bentonite has a high cation-exchange capacity and can affect the chemistry of water that comes into contact with it. Portland cement is used to make cement grout. When Portland cement cures, it is highly alkaline and can affect the pH of ground water that comes into contact with it. Neat cement grout will shrink by at least 17% when it cures. The addition of bentonite to make a bentonite-cement grout significantly reduces the shrinkage problem. If neat cement grout or bentonite cement grout is used, the casing material should be either stainless steel or schedule 80 PVC due to the heat generated as the cement cures.

The materials available for an annular seal are not ideal. Although they can be used to make an impermeable seal, there is a chance they might affect ground-water quality in their immediate vicinity. This problem is mitigated if 2 ft of fine sand is placed in the annular space above the filter-pack material or native sand opposite the screen. This keeps the annular seal material from coming into contact with the water entering the well screen.

Many hydrogeologists place a 2- or 3-ft layer of bentonite pellets above the fine sand if the pellets will be below the water table. The pellets will swell and keep the grout material from entering the filter-pack material. If the top of the 2-ft fine-sand seal is above the water table, then 2 ft of granular bentonite may be placed prior to the addition of the annular seal.

8.2.6 Protective Casing

In order to provide physical protection for the investment in a costly monitoring well, as well as to protect from vandalism by individuals accidentally or intentionally putting foreign fluids and objects into a monitoring well, a locking protective steel casing or well vault is needed.

A protective casing extends several feet above the ground surface. It extends above the top of the monitoring well and has an inside diameter sufficiently large so that the hydrogeologist can reach inside and unscrew a cap from the monitoring well. It is set into a surface cement seal. For monitoring wells installed in freezing climates, a drain hole at the bottom of the surface casing is desirable to prevent accumulation of moisture that could freeze in the annular space between the protective casing and the monitoring well. (The author has seen a stainless-steel monitoring well casing pinched shut by water that accumulated in a protective casing without a drain hole and then froze!)

In some applications, it is not practical to have a monitoring well that extends above ground—for example, in the driveway at a gas station. There are small well vaults available that can be used for protection for monitoring wells. However, they should be in places that are not going to flood; otherwise floodwaters could enter the aquifer via the monitoring well. If a well vault is used in a gas station or similar location, it should be clearly marked and should be distinctive from the fillers for underground storage tanks so that an inattentive person doesn't try to fill it with gasoline! A locking well cap without a vent hole should also be used.

8.2.7 Screen Length and Setting

The hydrogeologist must decide on the length of the screen and the depth to which it will be set, based on the objectives of the monitoring program. Objectives could include monitoring the position of the water table, measuring the potentiometric head at some depth in the aquifer, collecting representative water samples from various depths in the aquifer, and detecting both light and dense nonaqueous phase liquids. Moreover, monitoring might be intended to detect the migration of ground water containing contaminants into an aquifer or evaluating the effectiveness of removing contaminants from an aquifer. All might require different approaches.

To monitor the position of the water table or to detect the presence of LNAPLs, the screen must be set so that it intersects the water table. The screen must be long enough to intersect the water table over the range of annual fluctuation. In addition, the screen must be long enough so that when the water table is at its greatest depth below the land surface, there is enough of the screen remaining below the water table to contain sufficient water for a water sample. A water table monitoring well will also be able to detect the presence of light nonaqueous phase liquids. In most applications the minimum length of the screen for a water table–monitoring well is 10 ft with 5 ft above and 5 ft below the water table. If the water table has more than 5 ft of annual fluctuation, a longer well screen is needed. However, some states specify a maximum screen length of 10 ft. Figure 8.6 shows examples of incorrect (a and b) and correct (c) placement of a multipurpose monitoring well intended to measure the position of the water table, detect floating nonaqueous phase liquids, and collect water samples from the upper part of the aquifer.

If the purpose of a monitoring well is to measure the potentiometric pressure at some depth in the aquifer, then the well is called a **piezometer.** A piezometer should have a relatively short screen length, 2 to 5 ft, so that the pressure that is recorded is representative of only a small vertical section of the aquifer. A piezometer can also be used to collect ground-water samples that are representative of a small vertical section of the aquifer.

Monitoring wells utilized to collect ground-water samples should be designed with respect to a specific ground-water monitoring goal. The concentration of ground-water contaminants can vary vertically. If a monitoring well has a long well screen, it has a greater probability of intersecting a plume of contamination. However, a water sample taken from such a well may draw water from both contaminated and uncontaminated parts of the aquifer, resulting in a reported concentration that is less than that of the ground water in the plume. This is illustrated in Figure 8.7.

The collection of such unrepresentative water samples may have serious implications for the implementation of ground-water regulations. In monitoring ground water in order to find the actual concentration of contaminants in a plume, it may be necessary to use several piezometers screened at different depths at the same location. This is expensive, not only due to the initial cost of the wells but also due to the costs of multiple chemical analyses for each round of sampling. However, such a configuration

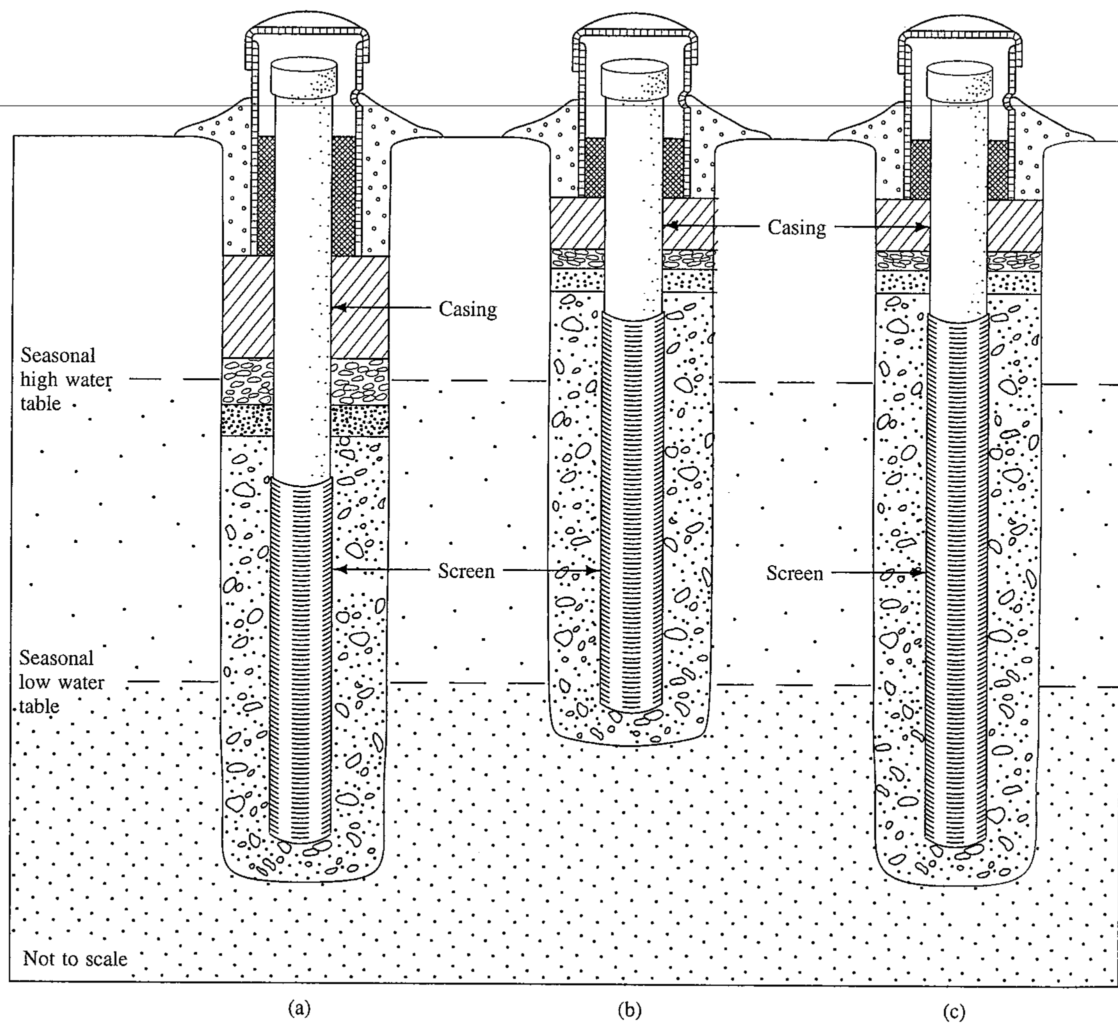

FIGURE 8.6 (a) Incorrect placement of water table–monitoring well screen. Seasonally high water table is above the top of the screen and floating, nonaqueous phase liquids would be above the screen and not detected. (b) Incorrect placement of water table–monitoring well screen. Seasonally low water table is so far down in well that there is not enough water in well to collect a sample for chemical analysis. (The water table elevation could still be determined.) (c) Correct length and placement of water table–monitoring well screen.

will yield the greatest amount of information about the hydraulic head as well as the water quality.

If a monitoring well is intended to serve as warning that a plume of contamination is escaping from a potential source, then it should be screened in the most permeable parts of the aquifer. Ground water and contaminants that it may be carrying not only

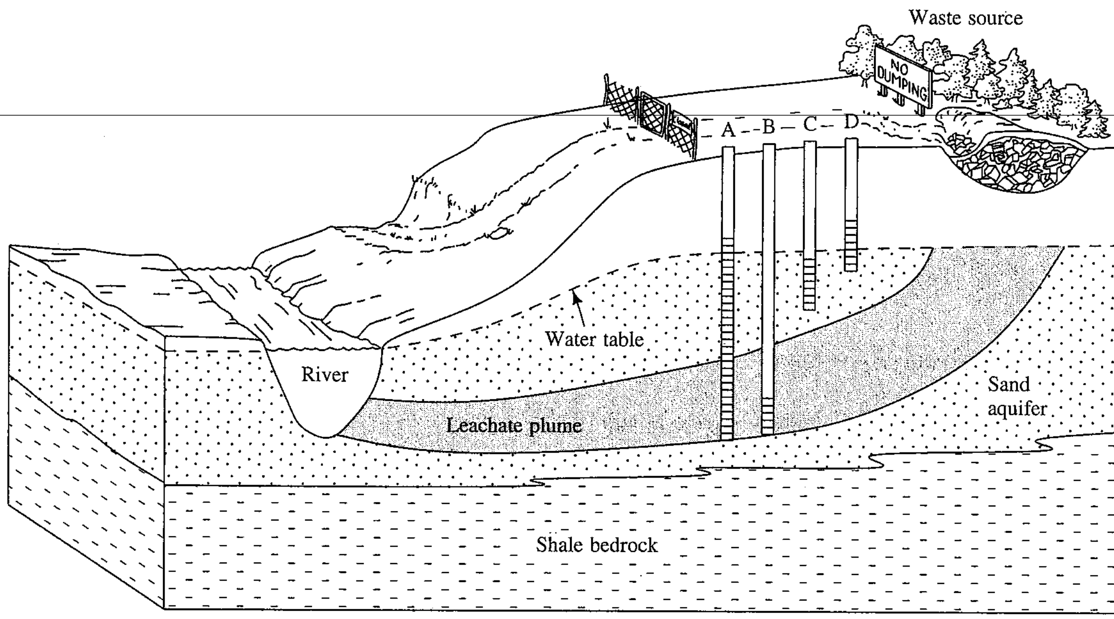

FIGURE 8.7 Effect of monitoring well—screen length on water-quality sampling. Monitoring well A is fully screened through the thickness of the aquifer. It intersects the plume of leachate but the reported concentration will be less than the actual concentration as water is withdrawn from both contaminated and uncontaminated parts of the aquifer. Piezometer B is also screened to intersect the plume of leachate. The reported concentration will be representative of the leachate. Piezometer C and water table monitoring well D don't intersect the plume, indicating that it is deep in the aquifer.

preferentially travel through the most permeable material but travel faster there as well. Hence, the leading edge of a plume of contamination will follow the most permeable pathway.

If the plume of contaminated water is following a zone or direction of high hydraulic conductivity, it may flow in a direction that is not parallel to grad h. This may mean that the location of the plume is not exactly down-gradient from the source.

On the other hand, if an aquifer is contaminated and a monitoring well has been installed to monitor the progress of a remediation effort, the well should not be screened in the most permeable part of the aquifer. In pump and treat systems, the water will preferentially travel through and flush out the more permeable zones. A well screened in a permeable zone may indicate that the aquifer is rapidly being cleaned, but in fact less permeable zones located nearby may still have high concentrations of contaminants that have yet to be removed.

8.2.8 Summary of Monitoring Well Design

Figure 8.8 illustrates details of the final design of a water table observation well and a piezometer illustrating all the design elements discussed in this section.

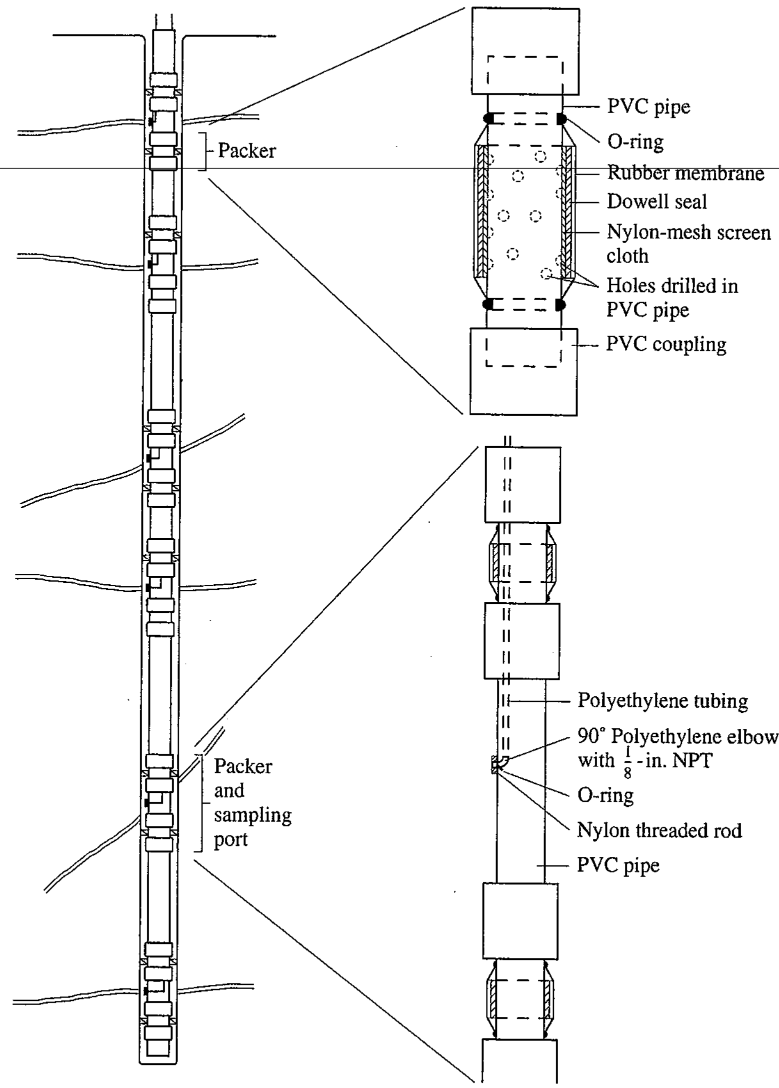

FIGURE 8.24 Multilevel ground-water sampling device for use in fractured rock aquifers. *Source:* J. A. Cherry and P. E. Johnson, *Ground Water Monitoring Review* 2, no. 3 (1982):41–44. Used with permission. Copyright © 1982 Water Well Journal Publishing Co.

8.10 Well Sampling

8.10.1 Introduction

After a monitoring well has been designed, installed, and developed, the next step is to collect a water sample. The water sample should be representative of the water in the formation; that is, the sampling techniques should collect water from the aquifer and not from water that has been standing in the well casing or screen. In addition, the sampling device should provide a sample that has not been altered by the sampling process and should not cause cross contamination.

8.10.2 Well Purging

Water that has been standing in the well has been in contact with atmospheric gases and the well casing and screen. This contact can affect the water chemistry. Oxygen can diffuse into the water and dissolved gases can volatilize or oxidize. Trace elements may be leached from the well casing. Organics may be sorbed by the well casing. In order to be sure that the water being drawn in to the sampling device comes from the aquifer, the well must be purged of standing water prior to sampling. The goal of purging is to remove all the water that has been standing in the well. The volume of water that must be removed to accomplish that goal depends upon the method of purging and formation permeability.

The first step in well purging is to measure the depth of water in the well, the total well depth, and the inside diameter of the well casing. These measurements are used to compute the volume of water standing in the casing. If a well is purged by a method that withdraws water from the top of the water column, then theoretically only one well volume needs to be withdrawn. For example, purging with a bailer that is lowered slowly into the well to a depth no greater than the length of the bailer will remove water only from the top of the column. If a pump is used to purge the well, the pump intake should be as close as possible to the top of the water column. Although one well volume would theoretically remove all the standing water, good practice suggests that at least three well volumes should be removed to be sure that the standing water in the casing and screen is totally removed. This also removes water from the filter-pack area. If a well is bailed dry, or nearly so, it is not necessary to attempt to remove multiple well volumes. As soon as the well has recovered enough to contain sufficient sample volume, the sample should be collected.

If the pump intake is lowered to the level of the screen in the well during purging, then most of the water will come from the screen area, and an area of stagnant water will develop in the water column above the pump intake. Under such conditions up to five well volumes need to be pumped to remove all of the stagnant water in the well (Gibb, Schuller, and Griffin 1981). Keeley and Boateng (1987) advocate a staged technique when purging with a pump. The pump intake is lowered to just below the water surface at the beginning of the purging process and then is gradually lowered through the water column until it is at the screen zone, when purging is complete. Purging three well volumes with this technique should be adequate.

Electrical conductivity and pH can be monitored during the well-development procedure. If they vary widely during the well-purging process, this may mean that water from different sources is being withdrawn. If these values don't stabilize, this doesn't necessarily mean that the stagnant water hasn't been withdrawn from the well. There may be instrument drift, or the water quality in the aquifer may be changing as water from different parts of the aquifer is being withdrawn. If possible, the well should be purged until it is not turbid.

The water being purged from the monitoring well may be contaminated. If so, it must be properly disposed of in a treatment facility. For this reason, purging techniques that limit the amount of water withdrawn are desirable.

8.10.3 Well-Sampling Devices

There are a large number of sampling devices available for monitoring wells. They operate under different physical principles and designs and have different applications. Most are available in a variety of materials. The following is a partial list of available devices (Nielsen and Yeates 1985; Pohlmann and Hess 1988):

1. *Open bailer:* This device is a rigid tube with an open top and either a closed bottom or a check valve on the bottom. It is attached to a line and is lowered and raised by hand. It withdraws the sample from the top of the water column.

2. *Point-source bailer:* This device has a check valve on both the top and bottom and can be lowered on a line to a given depth below the surface, where the valves can be closed by a cable. It can collect grab samples from any depth in the water column.

3. *Syringe sampler:* A medical syringe or similar device is attached to a length of tubing and is lowered to a selected depth in the water column. A suction is applied to the tubing and the syringe, which was lowered in the "empty" position. The syringe fills as the water comes into the needle because of the vacuum being developed by the suction on the tubing.

4. *Gear-drive pump:* This device is similar to a traditional submersible electrical pump. There is a miniature electrical motor attached to the pump, which rotates a set of gears to drive the sample up the discharge line via positive displacement. A continuous flow of water under positive pressure is developed.

5. *Bladder pump:* This sampler has a rigid tube containing an internal flexible bladder. There are check valves on either end of the rigid tube. When the bladder is deflated, water enters the lower end of the tube through the check valve. When the tube is full, the bladder is inflated with an inert gas pumped down from the surface. The bottom check valve closes, the top check valve opens, and the water sample flows up the discharge line. When the bladder deflates, the water in the discharge line can't drain back into the rigid tube because of the check valve. The water is under positive pressure at all times and doesn't come into contact with the gas.

6. *Helical-rotor pump:* This pump has a submersible electrical motor. It rotates a helical rotor-stator, which drives water up the discharge line under positive pressure.

7. *Gas-drive piston pump:* A piston that pumps the water is driven up and down by gas pressure from the surface. The gas does not contact the sample.

8. *Submersible centrifugal pump:* A submersible electrical motor drives an impeller in the pump, which creates a pressure and forces the water up a discharge line.

9. *Peristaltic pump:* Unlike the others, this is a pump located at the land surface. It is a self-priming vacuum pump that can draw a water sample up tubing under suction. Loss of volatile compounds and dissolved gases may occur due to the vacuum developed.